Changes in Vegetation Cover of Yellowstone National Park Estimated from MODIS Greenness Trends, 2000 to 2018

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Abstract. Trends and transitions in the MODerate resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) time-series at 250-m resolution were analyzed for the period from 2000 to 2018 to understand recent patterns of vegetation change in Yellowstone National Park (USA). Statistical change in the NDVI time series was detected using the “Breaks for Additive Seasonal and Trend” method (BFAST). This structural change analysis showed that at least one breakpoint could be detected at 12% of the 250-m MODIS pixel locations within the YNP study area since the year 2000, but that the majority (about 70%) of NDVI breakpoints detected in vegetation greenness could be not be explained by the impacts of recent wildfires. Evidence further suggested that the 1988 wildfire burns did not pre-dispose vegetation cover in YNP to a higher number of abrupt negative shifts in NDVI since the year 2000. The wildfires of 1988 were associated with significantly higher NDVI recovery trends over the recent 18-year MODIS time series, compared to areas unburned in 1988. Locations on the Northern Range that showed the highest greening trends since 2000 were commonly located in sagebrush steppe-dominated vegetation communities growing at lower than 2500 m elevation. Results from NDVI trend analysis supported the hypothesis that years with relatively high snowpack water content, such as 2007-08 and 2010-11, were most closely associated with abrupt negative shifts in NDVI, but no findings strongly supported the supposition that vegetation cover in YNP is changing in greenness in association solely with warming in surface air temperatures or with extreme drought periods across the study region over the past two decades.

Keywords: Yellowstone***;*** MODIS NDVI; forest; shrublands; fires; BFAST

Introduction

Yellowstone National Park (YNP) is predominantly a young to middle-aged (30 to 200 years old) forested landscape (Despain, 1990), with sagebrush-steppe and grassland plant communities on the Northern Range (NRC, 2002), alpine meadows and wetlands, and hydrothermal plant communities around hot springs and in geyser basins. Climate change, wildfire, and insect outbreaks are considered to be the main drivers of vegetation cover change in YNP (Potter, 2015).

Since the wildfires of 1988, which consumed about one-third (2500 km^2) of YNP and created a mosaic of burn severity classes, there have been several notable changes in vegetation communities reported in published studies. On the Northern Range, stands of quaking aspen (*Populus tremuloides*) declined in the 20th Century, as mature stands died but were not replaced by young trees (Romme et al., 1995; NRC, 2002). The loss of aspens has been associated with intensive herbivory by elk (*Cervus elaphus*) in the winter months, which may have suppressed the growth of young trees (Kauffman et al., 2010). With the reintroduction of wolves (*Canis lupus*) in the mid-1990s, Painter et al (2016) reported that many aspen stands on the Northern Range are in the early stages of recovery, owing to increased predation on elk and decreased browsing on young trees.

Air temperature has warmed by nearly 1^{o} C in Yellowstone since the 1988 fires, and this warming may be affecting the geographic distribution of both plants and wildlife (Hansen et al, 2016). Warmer temperatures are accelerating the melting of mountain glaciers, reducing snowpack, and changing the timing, temperature, and amount of streamflow (YNP, 2018). With respect to vegetation cover, aspen trees have been more likely to grow at cooler, higher elevations. As an example, the 2000 Boundary Fire on the southern edge of YNP re-burned 12-year old lodgepole pines (*Pinus contorta var. latifolia*) and seedling aspens that had regrown after the 1988 fires. Young pines had not developed a seedbank before reburning. Thirteen years after the Boundary Fire, Hansen et al. (2016) observed that aspen density was five times greater than lodgepole pine density, and many young aspens were taller than 2 meters.

In rugged wilderness areas, satellite remote sensing has been used to effectively monitor greening or browning in forested landscapes (Amiro et al., 2000; Cuevas-Gonzalez et al., 2009; Casady and Marsh, 2010; Geremia et al., 2011; Potter et al., 2011). Notably, Goetz et al. (2005 and 2006) analyzed the seasonal and inter-annual variations of post-fire forest cover by using normalized difference vegetation index (NDVI) time-series across boreal North America and reported vegetation compositional changes consistent with early successional plant species and susceptibility to drought. Potter (2015) analyzed more than 20 years of Landsat 30-m NDVI for the YNP area and concluded that the detectable changes in ecosystem green cover since the wildfires of 1988 have been strongly dependent on periodic variations in annual snowpack water content.

To date, most of the studies cited above of gradual greening or browning of land cover in forest and grasslands of western North America have not included comprehensive structural breaks analysis, designed to simultaneously detect all major disturbances that can alter greening trend statistics and the conclusions about gradual change in vegetation cover density and forest or shrubland health. Gradual change analysis applied to a time series is designed to test for changes in the coefficients of a regression model, and generally assumes that there is just a single change under the alternative or that the timing and the type of change are known (Zeileis et al., 2002). A structural break can occur when a time series abruptly changes at a point in time. This change could involve a change in mean or a change in the other parameters of the process that control the time series. Detection of multiple breaks or disturbances in a time series of NDVI can occur in wilderness areas as a result of periodic wildfires, insect outbreaks, and/or from repeated cycles of extreme weather events.

The objective of this study was to detect both abrupt and gradual changes in vegetation cover throughout YNP since the year 2000 using the 250-m resolution regional MODIS NDVI record and structural change analysis. The overarching question posed in this analysis of the highest spatial resolution MODIS NDVI available, and the longest time series yet assessed, was "Is the vegetation cover in YNP declining or increasing in greenness (i.e., live biomass density) since the year 2000 in association with warming in surface air temperatures or with extreme drought periods across the study region". Statistical analysis of changes in the NDVI time series was conducted using the "Breaks for Additive Seasonal and Trend" method (BFAST, Verbesselt et al., 2010a and 2010b). Four potential causes of ecosystem disturbance, observed as negative (abrupt browning) breakpoints in the NDVI record, and subsequent regrowth patterns of green vegetation cover, were the focus of this study: (1) wildfire in forest areas burned in both

1988 and again during the MODIS data period of 2000 to 2018, (2) wildfire in forest areas that did not burn 1988 but did burn during the MODIS data period of 2000 to 2018, (3) extreme drought conditions over the period 2000 to 2004, and (4) extreme snowpack water content and delayed snowmelt during the spring-summer transition periods of both 2011 and 2014.

Study Area

YNP covers 8,980 km^2 and extends from elevations of 1540 m to 3760 m (NW corner coordinates: 45° 15' N, 111° 12' W; SE corner coordinates: 44° 5' N, 109° 49' W, Figure 1). Surrounding mountain ranges are the Gallatin Range to the northwest, the Beartooth Mountains in the north, the Absaroka Range to the east, and the Teton Range and the Madison Range to the southwest and west.

The montane zone in YNP is found between 1200 and 1800 m, and the subapline forest zone is located between 1800 and 2700 m, approaching timberline (Halbeck, 1987). The forests of YNP consist of five main conifer species (Kokaly et al., 2003): lodgepole pine (*Pinus contorta*), whitebark pine (*Pinus albicaulis*), Douglas fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*). Elevation and soil fertility are considered to be the two most important abiotic gradients controlling forest vegetation on the subalpine plateaus (Christensen et al., 1989). Non-forest vegetation is composed of four major cover types:

grassland, sagebrush steppe (shrubland), wet sedge and willow meadow, and alpine meadow.

The National Park Service (NPS) has reported that, due to climate change, wildfire seasons in YNP have recently expanded, and fires have increased in severity, frequency, and size. A series of wildfires in 2016 burned more acres than in any year in the last century except 1988 (Table 1). In particular, the Maple Fire that began in August, 2016 was located in young forested land that was burned in North Fork Fire of 1988. Large-scale disturbances like the Maple Fire have presented an opportunity for NPS managers and other researchers to observe fire return impacts on plant species composition and wildlife populations (YNP, 2018).

Methods

Climate data records

Two weather station locations within the study area provided daily average air temperature, precipitation amounts, and snow water equivalents (SWE) records dating back to the year 2000, namely the northeast entrance to YNP (45^{o} 00’ N, 100^{o} 01’ W) and Canyon (44^{o} 43’ N, 110^{o} 32’ W) stations (data available online at wrcc.dri.edu).

Fire boundary data from Landsat

Digital maps of burn area boundaries and classes at 30-m spatial resolution were obtained from the Monitoring Trends in Burn Severity (MTBS; www.mtbs.gov) project, which has consistently mapped fires greater than 1000 acres across the United States from 1984 to the present (Eidenshink et al., 2007). The MTBS project is conducted through a partnership between the U.S. Geological Survey (USGS) National Center for Earth Resources Observation and Science (EROS) and the USDA Forest Service. Landsat data have been analyzed through a standardized and consistent methodology by the MTBS project. The normalized burn ratio (NBR) index was calculated by MTBS using approximately one-year pre-fire and post-fire images from the near infra-red (NIR) and shortwave infra-red (SWIR) bands of the Landsat sensors, with reflectance values scaled to between 0 and 10000 NBR units.

$$NBR = (NIR – SWIR) / (NIR + SWIR)$$

Pre- and post-fire NBR images were next differenced for each Landsat scene pair to generate the dNBR severity classes.

MODIS Vegetation Index Time Series

NASA's MODIS (Moderate Resolution Imaging Spectroradiometer) satellite sensors Terra and Aqua have been used to generate a 250-m resolution NDVI (MOD13) global product on 16-day intervals since the year 2000 (Huete et al., 2002; Didan et al., 2016, Shao et al., 2016). The MODIS Collection 6 NDVI data set provides consistent spatial and temporal profiles of vegetation canopy greenness according to the equation:

$$NDVI = (NIR – Red) / (NIR + Red)$$

where NIR is the reflectance of wavelengths from 0.7 to 1.0 μm and Red is the reflectance from 0.6 to 0.7 μm, with values scaled to between 0 and 10000 NDVI units to preserve decimal places in integer file storage. Low values of NDVI (near 0) indicate barren land cover whereas high values of NDVI (above 8000) indicate dense canopy greenness cover.

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The MOD13 250-m vegetation indices (VIs) have been retrieved from daily, atmosphere-corrected, bidirectional surface reflectance. These MOD13 data sets were downloaded from the files available at modis.gsfc.nasa.gov/data/dataprod/mod13.php for time series analysis across the study area. The VIs were computed from MODIS-specific compositing methods based on product quality assurance metrics to remove all low quality pixels from the final NDVI value reported. Snow-covered, cloud and water pixels were identified and excluded using other MODIS atmospheric data masks. From the remaining good-quality growing season (May to October) NDVI values, a constrained view-angle approach (closest to nadir) then selected the optimal pixel value to represent each 16-day compositing period.

Elevation and Land Cover Map Layers

Digital elevation (in vertical meters) was derived from USGS (2016) mapping at 30-m ground resolution. Vegetation cover was mapped at 30-m ground resolution from the 2006 National Land Cover Dataset (NLCD; Homer et al., 2011; available at www.mrlc.gov). Wetland areas that covered less than a majority of 200 x 200-m resolution areas in the study area grid were too small to be matched consistently with MODIS 250-m NDVI and were therefore not discriminated as wetlands in the analysis. Pre-1988 forest age map layers were derived from Despain (1990).

Statistical Analysis Methods

The BFAST (Breaks for Additive Seasonal and Trend) methodology was applied to the MODIS NDVI monthly time series. BFAST was developed by Verbesselt et al. (2010a, 2010b) for detecting and characterizing abrupt changes within a time series, while also adjusting for regular seasonal cycles. A harmonic seasonal model is first applied in BFAST to account for regular seasonal phenological variations. BFAST next computes the Ordinary Least Squares Moving Sum (OLS-MOSUM) by considering the moving sums of the residuals after the harmonic seasonal model has been removed from the time series data values. MOSUM tests for structural change using the null hypothesis that all regression coefficients are equal i.e. every observed value can be expressed as a linear function with the same slope (Zeileis et al., 2002). If the null hypothesis is true, the values can be modeled by one line with that slope and the sum of residuals will have a zero mean. MOSUM compares moving sums of residuals to test the likelihood of the regression coefficient for a certain time period based on a user's input stating the minimum time between potential "breakpoints". A rejection of the null hypothesis indicates that the regression coefficient changes at that point in time.

The MOSUM uses a default *p*-value of 0.05, meaning that the probability of it detecting a structural change when none has occurred is less than 5%. If MOSUM does not detect some structural change with a confidence level of 95%, it returns a "no breakpoints" result. If MOSUM detects some structural change with a confidence level of 95%, it then processes the time series through a second test, which is used to determine where the breakpoints are located in time. The output of this function is a 95% confidence interval for each breakpoint (expressed as two date numbers that define a range).

For BFAST time-series analysis, MOD13 NDVI data values (2000 to 2018) were subsampled to include only the growing season values, during the low snow cover period of May 1 to October 1, leaving about 10 observations per year. If a "no data" value was present in the growing season MOD13 record, then the NDVI from the previous 16-day period was substituted.

Results

Trends in air temperature and SWE

Daily data plotted since beginning of the year 2000 from both the northeast entrance of YNP and at Canyon SNOTEL stations showed that, based on minimum winter air temperatures, 2005 and 2015 were the warmest years in the time series, whereas 2003 was the coldest year (Figure 2). The winters of 2008-09 and 2010-11 were the years with the highest SWE totals, whereas 2004-05 and 2009-10 were the driest overall. The combination of these records indicated that 2005 was the warmest and driest year in the past 18-years in YNP.

BFAST output results

Structural change in the NDVI time series as BFAST output results at four selected locations (Figure 3; locations in map Figure 4) were plotted to illustrate the changes in NDVI and potential breakpoint detection within large wildfire burn areas since the year 2000 (according to MTBS fire boundary records). All four BFAST results from within these relatively recent burned areas detected a breakpoint for the MTBS-reported year of wildfire ignition. There was an abrupt decrease of around 2500 NDVI units following the confirmed fire event in each case. For the two fire locations that burned in 2002 and 2006, the post-fire slope of the NDVI (*Tt*) fitted "trend" component was strongly positive until the end of the time series in early 2018, and in the case of the Magpie Fire, the post-fire trend recovered about 2000 NDVI units over the first ten years after this 2006 fire event, to approach pre-fire NDVI levels. In the cases of the two wildfires that started in 2016, BFAST detected a breakpoint starting about a year earlier, possibly owing to the peak growing season NDVI for the entire time series having been detected in 2014 and then declining notably into 2015 just prior to the fire year.

The outputs for BFAST's "noise" (*et*) component (Figure 3, plot bottom panels) provided the dates and magnitudes of both the largest positive and largest negative residuals (LPR and LNR, respectively) from the de-seasonalized and de-trended NDVI record. The LPR dates for the 2002 and 2006 fire locations were consistently clustered within two to three years post-fire, whereas he LPR dates for the 2016 fire locations were detected in the year following the fire. The LNR dates for all four of the selected locations were consistently clustered in the year 2011. The magnitudes of these LNRs were between -3000 -4000 and -6000 NDVI units. In all cases, the dates of LNR did not correspond to the MTBS-recorded dates of large wildfires, nor to the breakpoint timing detected in BFAST analysis.

Breakpoint frequency and locations

NDVI time series analysis detected at least one breakpoint at 12% of the 250-m resolution MODIS pixels within the YNP study area since the year 2000 (Figure 4). The distribution of outputs showed that one-third of all the breakpoint locations were detected with two or more abrupt NDVI change events over the 18-yr time series. About 62% of locations detected with at least one NDVI breakpoint were in vegetation cover classified in the NLCD as forested, followed by 27% in shrubland cover and 11% in herbaceous grassland cover. The majority of NDVI breakpoints were located at sub-alpine elevations higher than 2300 m.

With respect to the timing of NDVI breakpoints, the years 2010 and 2015 were detected with the highest number of abrupt changes in green vegetation cover (at > 15% in each of these two years), followed by the years 2007-2009 and 2013 with about 10% of all breakpoints in each of these four years (Figure 5). However, based on the BFAST output examples shown in Figure 3, a high fraction of negative breakpoints attributed to the year 2015 may have occurred at the locations of wildfires that ignited during the summer of 2016, but were detected as a strong pre-fire decline in NDVI late in the year 2015.

Slightly more than 30% of all MODIS pixel locations detected with at least one NDVI breakpoint since the year 2000 corresponded to a MTBS-recorded severely burned area from the wildfires of 1988. The proportion of all MODIS pixels detected with no NDVI breakpoints that also burned at high severity during 1988 was not significantly different from the 30% level, which indicated that the 1988 burns did not pre-dispose vegetation cover in YNP to a higher number of abrupt changes in NDVI since the year 2000.

Fire return impacts

BFAST results for the area burned within the perimeter of the 2016 Maple Fire and that was also severely burned during the 1988 North Fork Fire were compared to a section of the North Fork Fire area in a 1.5-km buffer zone just outside the MTBS-delineated perimeter of the Maple Fire, and also to all the small sub-sections of the Maple Fire burn that were not also burned in the North Fork Fire of 1988.

Results showed that the locations burned during both the Maple and North Fork Fires had a significantly higher ($p < 0.05$) positive NDVI trends over the 18-year MODIS time series compared to areas burned during the Maple Fire but not burned in the North Fork Fire about 28 years earlier, and more than twice as high compared to areas within the 1.5 km buffer zone that did not burn during either the Maple Fire or North Fork Fire (Table 2). Locations burned during both the Maple and North Fork Fires showed significantly different ($p < 0.05$) and less extreme LNR in the NDVI time series compared to areas burned during the Maple Fire but not burned in the North Fork Fire, and compared to locations that did not burn during either the Maple or North Fork Fires.

Area-wide greening and browning trends

For slightly more than 62% of the YNP study area, BFAST results showed positive (greening) NDVI trends between the years 2000 and 2018 (Figure 6). This majority percentage of greening pixels numbers was consistent across both locations detected with at least one NDVI breakpoint and those without any breakpoints. Greening trends across YNP were most commonly estimated at between +350 and +1000 NDVI units of gradual increase over 18 years (Figure 7).

As another means of assessment of the impacts of the 1988 wildfires on recent NDVI trends, areas burned by large wildfires between the years 2000 and 2016 and also burned during 1988 across the entire YNP study area showed a higher percentage of locations with positive greening trends than did areas burned between 2000-2016 and not burned during 1988 (Figure 8). This finding suggested that one effect of severe burning during the 1988 fires was to transform dense old-growth forest stands to near-zero NDVI levels, which in turn regrew slowly until the early to mid-2000s, when more recent fires of moderate severity in relatively young forest stands again reduced NDVI and re-set the vegetation regrowth cycle.

Areas with the most negative (browning) NDVI trends were clustered mainly within boundaries of two recent wildfires, namely the Sulfur Fire (2001) and the Broad

Fire (2002) (Figure 6). Another noticeable band of locations with negative 18-year NDVI trends was detected in steep forested terrain below Sepulcher Mountain along the Reese Creek drainage of the Yellowstone River near Gardiner, Montana (between 45.05^{o} N -110.82^{o} W and 45.00^{o} N -110.72^{o} W at elevations between 2000 and 2200 m), outside of any recent burned area. NDVI showed a gradual decline in these upper watershed forests from 2001 to 2005 and the LNR date occurred in early in the growing season of 2014.

For locations where no NDVI breakpoints were detected, the majority of LNRs after the year 2000 were detected within dates spanning the years 2008-2010 (Figure 9), a period within which winter seasons were recorded with the highest SWE totals. For locations where at least one NDVI breakpoint was detected, the majority of LNRs fell instead within the period of 2001-2003. The map of dates for the LNR detected in the NDVI time series (Figure 10) showed extensive contiguous areas of the Lamar River and Yellowstone River valleys with LNR dates detected during the 2010-2011 period. At higher elevation sagebrush shrubland locations of these large river valleys, LNR timing was commonly detected during the 2001-2004 period.

Focus on the Northern Range of YNP

Several unburned (since the year 2000) locations of interest were examined more closely for recent NDVI shifts detected on the Northern Range of YNP (Figure 11). At a location representative of the Hellroaring Creek sub-basin about 9 km outside the YNP boundary to the north, there was a change in the NDVI seasonal cycle starting in 2008, from a more evergreen profile to a more deciduous-leaf seasonal profile with lower late-season NDVI. This location increased gradually in green plant cover after 2008 (Figure 12). Along the Yellowstone River valley within the Elk Creek sub-basin, NDVI breakpoints were detected at the end of 2008 and again in 2013, the former due to an abrupt negative shift and the latter due to an abrupt positive shift in green cover. This repeat breakpoint pattern resulted in no net change in NDVI level at this location over the 18-year time series.

At a location representative of the Lower Slough Creek sub-basin, a single negative NDVI breakpoint of moderate magnitude was detected in 2011 (Figure 12). This abrupt deviation was followed by a gradual greening trend until 2018. The middle and upper reaches of Slough Creek, 6 to 12 km north of the YNP boarder, were among the areas that showed the highest greening trends since 2000 across all of the Northern Range. These areas were commonly located in sagebrush steppe-dominated vegetation communities growing at lower than 2500 m elevation.

At a location representative of the Soda Butte Creek sub-basin, no NDVI breakpoint was detected since 2000 and a gradual browing trend was plotted in the evergreen seasonal profiles over the entire time series. Scattered locations of strong browning trends were detected along the lower Soda Butte Creek drainage above the confluence with the Lamar River in unburned (since 2000) conifer forest-dominated communities at around 2200 m elevation.

At a location representative of the Blacktail Deer Creek sub-basin and the Amethyst Creek sub-basin of the Lamar River drainage, one negative NDVI breakpoint of moderate magnitude was detected during the 2007-2008 period (Figure 12). These deviations were followed by a gradual greening trend until 2018 and more deciduous-leaf seasonal profiles until 2014.

Discussion

Nearly two decades of continuous MODIS NDVI data can provide consistent large-scale indices of vegetation disturbance and transitions (gradual greening or browning) in remote locations of the northern Rocky Mountains. This is the first such study to use BFAST analysis on the highest resolution MODIS NDVI at 250-m resolution to generate detailed indicator maps of recent vegetation change over YNP and the Northern Range.

To put the present study within the context and general findings of previous similar studies, de Jong et al. (2102) analyzed trends in NDVI satellite time series using the BFAST procedure and detected both abrupt and gradual changes in large parts of the world, especially in shrubland and grassland biomes where abrupt greening was often followed by gradual browning. In a study using BFAST and MODIS NDVI to detect forest clearing in France, Lambert et al. (2015) detected a yearly period characterized by high negative breakpoint counts with relatively small magnitudes in NDVI decline, and attributed these changes to the direct impact of summer drought and heat wave on the vitality of the forest stands. In subsequent years, period of high negative breakpoint count with relatively large magnitudes in NDVI decline were attributed to forest clear-cutting.

Results from this YNP MODIS study revealed that the majority (about 70%) of NDVI breakpoints detected in vegetation greenness over the years 2000 to 2018 could not be explained by the impacts of recent wildfires, typically affecting shrubland and forested ecosystems at sub-alpine elevation zones in YNP. It could be further inferred that the 1988 burns did not pre-dispose vegetation cover in YNP to a higher number of abrupt changes in NDVI since the year 2000.

Instead, winters with relatively high snowpack and SWE, such as 2007-08 and 2010-11 were more closely related to abrupt negative shifts in NDVI. These seasons of late snowmelt with high water content followed a period of historically low SWE in the Northern Rockies (Pederson et al., 2010). Potter (2015) likewise reported that unprecedented periodic decline in SWE over the years 1985 to 2005 had significant impacts on green vegetation cover, as determined from Landsat image analysis across unburned ecosystems of YNP. Effects were acute during the year 2001, during which the peak yearly SWE levels declined to an historic low of -1.4 standard deviations of the long-term mean SWE.

The impacts of vegetation reburning by large wildfires of 2016 at locations in YNP that were also severely burned during wildfires of 1988 were found to result in significantly higher NDVI recovery trends over the 18-year MODIS time series, compared to areas burned during 2016 but not burned in the North Fork Fire of 1988, and more than twice as high compared to locations that did not burn during either 1988 or 2016. These findings support the hypothesis that severe forest burning during the 1988 fires reduced NDVI levels to nearly zero greenness in many formerly dense old-growth forested stands in YNP, a pattern confirmed by Franks et al. (2013) who used a time series of Landsat satellite imagery to compare NDVI with field-based data of post-fire stand structure from the 1988 YNP fires; and subsequently these high burn severity areas recovered live green cover gradually for the following 28 years at a rate more than twice as rapid as adjacent locations that did not burn in the 1988 wildfires.

The 18-year time series results for NDVI on the Northern Range identified numerous locations where transitions to more deciduous-leaf seasonal profiles, i.e., steeper than average declines in late season green cover than in preceding years. This observation would be consistent with increased aspen regrowth, most notably after the 2007-2008 growing seasons, which was the start of a period of deeper snowpacks and higher than average SWE than in the previous decade. It is also consistent with the findings of Painter et al (2016), who reported that many aspen stands on the Northern Range are in the early stages of recovery. However, the relative importance of reduced elk browsing on young trees versus the accumulation of higher than average SWE than in many previous years as the primary explanation for these increased deciduous-leaf seasonal profiles cannot yet be determined, and may be equally probable.

It is noteworthy that the region-wide drought of 2001 to 2005 could not be strongly associated with significant shifts in NDVI across most the Northern Range, or within YNP as a whole. The yearly distribution of the numbers of NDVI breakpoints indicated that the period 2001 to 2005 had the lowest frequency of breakpoints within the 18-year MODIS time series. Nonetheless, locations where the 2001 to 2005 drought period was associated with sustained declines in NDVI were identified along Lamar River and Yellowstone River valleys and in the Sepulcher Mountain drainages of the Yellowstone River near Gardiner, Montana.

The magnitude and timing of LNR values from BFAST analysis of satellite NDVI can provide a new and useful metric of abrupt declines in ecosystem green cover that commonly recover rapidly from whatever agent of disturbance was present at the time of the LNR. The majority of LNRs of NDVI within YNP were detected within the period of 2008-2010, which corresponded to relatively high annual precipitation totals and within which winter seasons were recorded with the highest SWE totals in decades. On an annual basis, the highest number of NDVI breakpoints detected per year was during 2010. One can hypothesize from this evidence that extreme LNR events in YNP have been associated with late spring thawing of relatively deep snowpacks and elevated levels of surface moisture in riparian zones and floodplains of the Lamar and Yellowstone Rivers.

Conclusions

The results from structural change analysis showed that majority of vegetation cover in YNP was detected with positive growing season NDVI trends since the year 2000, mainly in areas classified as young forests and regrowing (from recent fire disturbance) woodland cover. Findings suggested that severe burning during the 1988 fires transformed dense old-growth forest stands to low NDVI levels, and these former forests recovered live green cover at a relatively high rate for nearly 30 years, even in areas that burned again after the year 2000. Late spring thawing of relatively deep snowpacks was the factor most closely associated with abrupt negative shifts in NDVI across YNP. Using the highest resolution MODIS data at 250-m resolution and an 18-yr time series to generate detailed map results over remote areas of YNP, new insights and metrics of change can be derived from BFAST statistical outputs.

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Table 1. Ten largest wildfires in YNP and the Northern Range since 1999 from the MTBS.

Fire Name	Acres	Year
Maple	103,194	2016
Wicked Creek	22,195	2007
Berry	20,783	2016
East Complex	18,093	2003
Columbine 1	17,290	2007
Buffalo	13,707	2016
Big Creek	13,424	2006
Miner Paradise	12,210	2013
Arnica	11,0171	2009
Le Hardy	9,225	2008

Table 2. Comparison of BFAST results for areas burned within the Maple Fire perimeter of 2016 and also with the North Fork Fire perimeter of 1988. NDVI averages are shown, followed by two standard errors of each average value in parentheses.

Burned cover class	*N* (pixel no.)	NDVI Trend (per 18 yrs)	NDVI Average (18 yrs)	NDVI LNR Average
Maple burned and North Fork burned	2520	+1363 (35)	4983 (34)	-1582 (32)
Maple burned and North Fork unburned	1272	+867 (37)	4920 (42)	-1720 (41)
Maple unburned and North Fork burned	1475	+1282 (45)	4648 (57)	-1939 (48)
Maple unburned and North Fork unburned	917	+689 (50)	5119 (47)	-1942 (51)

Figure Captions

Figure 1. Yellowstone National Park and the Northern Range study area in shaded elevation relief. Burned area perimeters from wildfires of 1988 were delineated in grey solid lines, whereas perimeters from wildfires recorded between 2000 and 2016 were delineated in black solid lines.

Figure 2. Climate data time series from 2000 to 2017 for two weather stations in YNP.

Figure 3. BFAST plot outputs for four selected burned area locations (labelled in Figures 4) between the years 2000 and 2018 covering 250-m MODIS pixels in YNP. *Yt* is the time-series MODIS NDVI value; St is the fitted seasonal component; *Tt* is the fitted trend component; *et* is the noise component (Verbesselt et al., 2010a), Statistical breakpoints ($p < 0.01$) are identified by vertical dashed lines. Year numbers on the horizontal axis start at 1 in early 2000 and end in early 2018.

Figure 4. Study area map of the number of NDVI breakpoints detected in BFAST MODIS time series analysis over the period 2000 to 2018.

Figure 5. Yearly distribution of the numbers of NDVI breakpoints detected in BFAST MODIS time series analysis over the period 2000 to 2018

Figure 6. Study area map of the NDVI trend (slope of linear regression line) detected in BFAST MODIS time series analysis over the period 2000 to 2018.

Figure 7. Distribution of NDVI trend (slope of linear regression line) the MODIS time series analysis over the period 2000 to 2018 for locations detected with breakpoints (top) and for locations with no breakpoints detected (bottom).

Figure 8. Distribution of NDVI trend (slope of linear regression line) the MODIS time series analysis over the period 2000 to 2018 for locations within areas burned during the period 2000-2016 and also burned during 1988 (top), and for locations within areas burned during the period 2000-2016 and not burned during 1988 (bottom).

Figure 9. Yearly distribution of the LNR of NDVI detected in BFAST MODIS time series analysis over the period 2000 to 2018 for locations detected with breakpoints (top) and for locations with no breakpoints detected (bottom).

Figure 10. Study area map of the year of LNR detected in BFAST MODIS time series analysis over the period 2000 to 2018.

Figure 11. Map for the Northern Range of NDVI trend (slope of linear regression line) detected in BFAST MODIS time series analysis over the period 2000 to 2018. Locations labelled for BFAST plot outputs in Figure 12.

Figure 12. BFAST plot outputs for selected locations (labelled in Figure 11) of contrasting NDVI trends on the Northern Range between the years 2000 and 2018. Sub-basin and creek drainages were determined from Seaber et al. (1987).